Physical oceanography in Croatia, 1999–2002

Report submitted to the International Association for the Physical Sciences of the Ocean of the International Union of Geodesy and Geophysics

Between 1999 and 2002 physical oceanographic research in Croatia has been carried out mainly in the following institutions: Institute of Oceanography and Fisheries, Split; Hydrographic Institute of the Republic of Croatia, Split; Center for Marine Research, Rudjer Bošković Institute, Rovinj and Zagreb; and Andrija Mohorovičić Geophysical Institute, Faculty of Science, University of Zagreb.

Altogether, 19 investigators (13 PhD's, 2 MSc's and 4 BSc's), supported by a modest technical staff, were involved in the research. Three research vessels (*Bios, Hidra, Vila Velebita*) were used in the field work. The oceanographic equipment included several CTD probes (Seabird, Idronaut) and thermistor chains (Aanderaa), a number of current meters (Aanderaa RCM's and RDI ADCP's), tide gauges (Ott analogue instruments and Aanderaa, Ott and Parascientific digital instruments), wave gauges (Datawell, Seabird), and automatic meteo-oceanographic stations (Aanderaa). All institutions had a local computer network with a mainframe computer and a series of personal computers, connected to Internet through Carnet (Croatian Academic Research Network). Moreover, a computer cluster has been acquired, to be used in fine-scale modeling of Croatian coastal waters.

During the four-year interval considered some previously established measurement programs were maintained and some new were started. Thus, hydrographic data were collected on a monthly or seasonal basis all along the east Adriatic coast, as well as along some cross-shore transects (Rovinj-Po, Split-Gargano). Current measurements were performed, mostly on the short-term basis, in the framework of various hydrotechnical projects (Kvarner, Zadar and Šibenik Archipelago, Split, Brač and Mljet Channels, Zrmanja and Krka Estuaries, Dubrovnik area). Tide-gauge measurements were continued at a previously established network of seven stations (Rovinj, Bakar, Zadar, Split-Marjan, Split-Harbour, Sućuraj, Dubrovnik), with some new stations being established recently (Plomin, Susak, Split-Lighthouse, Ploče). Sea-surface temperature was measured daily at a number of coastal stations. Last but not least, automatic meteo-oceanographic stations were maintained at three locations (Veli Rat, Punta Jurana, Sveti Ivan) in order to enable air-sea fluxes to be determined for use in the oceanographic research.

Over the preceding four years Croatian institutions participated in several national projects, in bilateral programs (with Italian partners: ADRICOSM, MAT; with American partners: EACE), and in programs supported by Euro-

pean Community (COST40, ESEAS, MAMA, SEASEARCH). Croatian physical oceanographers also took part in the IOC assemblies, GOOS and GODAR meetings, as well as in a number of international conferences and workshops.

The work done is documented in the publications the list of which is attached to this report. The list contains scientific papers, conference communications published *in extenso*, books and theses. Some attention was paid to fluxes across the air-sea interface. On the basis of monthly averaged coastal meteorological data long-term series (1966–1992) of surface heat, water and buoyancy fluxes in the north Adriatic were computed (Supić, 2000, Supić and Orlić, 1999). These have subsequently been correlated with the current speed (Supić, 2000, Supić et al., 2000, 2001) and with the characteristics of water masses in various areas (Vilibić, 2002a, b, c, Vilibić and Orlić, 2001a, b, 2002). Thus, for example, it was found that the occurrence of the Istrian Coastal Countercurrent during summer in the north Adriatic is more probable if in the preceding winter the transfer of heat from the sea to the atmosphere was lower than usual. Moreover, it was established that the outflow of dense water from the Adriatic shelf usually occurs during spring, four months after weakening of the Po River discharge and two months after high surface buoyancy loss in the north Adriatic. Surface fluxes were also calculated over several months only but using daily or even ten-minute values of input parameters (Supić and Orlić, 1999, Dadić et al., 2001a, Grbec et al., 2001). These calculations showed that the winter transfer of heat from the sea to the atmosphere is dominated by short episodes which last only several days and which are related to the bora wind blowing above the Adriatic. Bone and Grbec (2001) considered a simple solar radiation model to be used in numerical modeling of the Adriatic Sea.

A number of publications dealt with the open Adriatic hydrography and current field variability. Long-term (1966–1992) changes in hydrographic conditions at a station in the open north Adriatic were discussed and qualitatively related to long-term changes of air-sea fluxes (Supić and Ivančić, 2002). Seasonal variations of current field components (inertial oscillations, wind-driven, geostrophic and residual currents) in the north Adriatic were analyzed on the basis of extensive data set (Krajcar, 2001). Bora wind influence on the north Adriatic was studied by the empirical analyses and the meteorological and oceanographic numerical modeling (Beg Paklar, 2000, Beg Paklar et al. 1999, 2001a). Empirical analyses were made on the basis of the current-meter data, satellite sea-surface temperatures and trajectories of satellite-tracked drifters. Numerical simulations were performed with Princeton Ocean Model (POM) forced with wind stress and heat fluxes calculated by bulk method from the winds, air temperatures and humidities obtained by Mesoscale Model 5 (MM5) and ALADIN model and sea-surface temperatures from the oceanographic model as well as with river discharges. The numerical experiments revealed that the offshore spreading of the cold and less saline water from the west coastal area in the form of the narrow fil-

ament after the bora events is a result of a joint action of three external forcings: wind stress, surface heat flux and river discharge, and none of these can be neglected in simulating the observed pattern. These studies represent the first attempt to numerically simulate response of the Adriatic shelf water and the Po River plume to realistic space- and time-variable atmospheric fields, with resolution which enables one to resolve alongshore variability in the wind field and to follow the temporal evolution and decay of the current field. Leder (2002) reported on the occurrence of internal waves near the steep shelf break off the island of Lastovo during summer season, and hypothesized that the waves are excited primarily by the wind action. Transparency decrease at the open sea station Stončica was motivation for including different optical water conditions in the numerical simulations (Beg Paklar et al., 2001b). Different optical types used resulted in changed vertical thermal structures, and the differences, after few days of integration, were higher for the summer than for the winter simulation. Physical studies found application in the investigation of the Adriatic ichthyofauna (Dulčić and Grbec, 2000, Dulčić et al., 1999, Grbec et al., 2002) and in the projects concerned with biodiversity preservation (Požar-Domac et al., 2000).

Coastal oceanography is a discipline that plays a significant role in the Adriatic investigations. Orlić et al. (2000), by comparing CTD data collected before and after a precipitation event and current-meter data measured during the event, demonstrated that the Velebit Channel is strongly influenced by fresh-water input. Leder et al. (1999b) showed that the east part of the Kaštela Bay is influenced more by the wind forcing than the fresh-water outflow. Basic statistical analysis of all available current data from the Kaštela Bay for a period between 1953 and 1990 showed importance of the sirocco wind in generating circulation in the bay (Zore-Armanda et al., 1999a, Beg Paklar et al., 2002). Strong episodes of sirocco reverse the estuarine circulation in the bay inlet. In the bay interior sirocco-induced surface currents turn to the right of the wind direction under the influence of the Coriolis force. Most empirical findings were found to agree with the previously published results of 3D numerical modeling of the Kaštela Bay wind-driven dynamics (Orlić et al., 1999). Some other processes in the Kaštela Bay were modeled by Bone et al. (1999) and by Morović et al. (1999, 2001). Vilibić and Orlić (1999) documented occurrence of barotropic surface seiches (period 2.2 h) and baroclinic Kelvin waves (period 4 days) trapped during the summer season in the semi-enclosed channel off Zadar, by analyzing current-meter series at a large number of stations as well as tide-gauge data collected at Zadar. A number of papers dealt with the physical parameters relevant for the positioning of submarine wastewater sewage disposals off the coastal Croatian cities (Barić et al., 2000, Bojanić et al., 1999, Leder et al., 2000, Smirčić et al., 2001, Vilibić et al., 1999c). Experience gained while analyzing physical phe-

nomena was on several occasions usefully employed in the study of biogeochemical processes (Burić et al., 1999, Viličić et al., 1999).

Sea level also attracted interest of Croatian physical oceanographers over the preceding four years. In a series of publications response of the Adriatic to the planetary-scale atmospheric forcing has been considered (Pasarić, 2000, Pasarić and Orlić, 2001a, b, Pasarić et al., 2000). By applying methods of multiple correlation and regression analysis on the air-pressure and wind data on one hand and the sea-level data on the other it was shown that the previously observed departures from the inverse-barometer effect are due to the wind forcing. Moreover, a simple statistical model was developed in order to demonstrate that in multiple-input linear models with mutually correlated inputs small errors in one of the inputs produce biased estimates of all the response parameters. Climatology of the Adriatic seiches and their role in the appearance of extreme sea levels were examined in detail by Vilibić (2000, 2001). Raicich et al. (1999) considered the Adriatic fundamental mode as recorded in December 1997 at a number of stations distributed along the east coast. Vilibić and Mihanović (2001, 2002) studied the seiches appearing in the Split harbor by examining the data collected at MedGLOSS station recently located there and by using 2D barotropic numerical model. The installation of MedGLOSS station and preliminary analysis of the data was described in the paper by Vilibić et al. (2001). Furthermore, sea-level oscillations in the area of nearby Kaštela Bay were analyzed by Vilibić et al. (1999a), covering the periods from a few hours to decadal ones. Extreme oscillations in the Adriatic were subject of the paper by Vilibić et al. (1999b), whereas Vilibić et al. (2000) considered the impact of storm surges on the coastal infrastructure by analyzing transient episodes (storm at Split on 20 November 1999) and climatological data (1955–1997). An improved formulation of the open-boundary conditions for the Adriatic tidal model was given by Bobanović et al. (2000), and the Adriatic tides were subsequently investigated by Janeković (2001) using numerical simulations and data analysis. In two papers sea-level variability was related to land movements. Orlić and Pasarić (2000) showed, on the basis of tide-gauge data, that tectonic movements bring about a rising of the middle and south Adriatic coast relatively to the north Adriatic coast. Herak et al. (2001) used data and 2D model to show that the Makarska earthquake of 1962 generated a tsunami in the area and that initial disturbance was due to the subsidence of the foot wall of the seismogenetic fault.

Wind waves were considered in several papers. Leder et al. (1999a) estimated maximum wave height of 13.6 m to appear once in 100 years; the result stemmed from the data collected in the years 1978–1986 and 1992 at the waverider buoy located in the open north Adriatic. The analyses of extreme wave episodes based on selected situations were additionally documented by Pršić et al. (1999) and by Smirčić and Leder (1999). Finally, Smirčić et al. (2000) united existing surface wave analyses done for the north, middle and south Adriatic and made an intercomparison of the extreme wave height estimations.

In order to facilitate all these studies procedures for validation, analysis and presentation of oceanographic data were developed (Dadić, 2000, 2001, Dadić and Ivanković, 1999, Dadić et al., 2001b), and Marine Environmental Database of the Adriatic Sea (MEDAS) using Oracle 9i RDBMS and ArcView GIS programming tools was implemented (Ivanković et al., 2000).

Over the past four years several Adriatic-related topics were reviewed by Croatian investigators. Zore-Armanda et al. (1999b) considered classical data on hydrographic characteristics and currents, whereas Gačić et al. (2001) contrasted early findings on the Adriatic physical processes with the results based on modern *in situ* and remote measurements. Orlić (2001a) showed that the Adriatic sea-level variability is controlled by a number of physical phenomena (tides, storm surges and seiches, planetary-scale waves, seasonal and year-to-year variability, interdecadal variability, long-term changes) and reviewed the studies done on each of them. Furthermore, Orlić (2001b) presented a century of research of wind-related dynamics of Croatian coastal sea, distinguishing between direct response of the sea to the wind forcing and barotropic and baroclinic free waves. In the book by Penzar et al. (2001) the review was extended to the air-pressure forcing of the Adriatic, and a section was written on the temperature of the Adriatic Sea and its dependence of the air-sea heat flux, advection and mixing. Finally, Orlić (2002) overviewed development of physical oceanography in Croatia, starting with the first treatise on tides published in 1528.

Overall, the level of scientific activity of Croatian physical oceanographers in the 1999–2002 interval seems to be quite similar to that achieved during the four-year intervals preceding it and described in the previous reports to the International Association for the Physical Sciences of the Ocean*. Recently, intensive cooperation has started between Croatian researchers and their colleagues abroad, resulting in some extensive field programs and state-of-the-art modeling of the Adriatic dynamics. The effects of this cooperation should become evident in future reports.

Acknowledgement – Drs. B. Grbec, N. Supić and I. Vilibić kindly supplied information on physical oceanographic activities of their institutions.

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Mirko Orlić